CRG

Frpsrvlwh#Uhsolfd#Pluuruv iru# Oljkwzhljkw#Vsdfh0Edvhg#Rswlfv#

Vwhskhq#Ylqlqj#

Frqhuvwrqh#Uhvhdufk#Jurxs/#Lqf1

Gd|wrq#RK#78773

<6:165314;::

)

Gu1#Gdylg#Prohqkdxhu

Dlu#Irufh#Uhvhdufk#Oderudwru|

4;#Dxjxvw#5337

Applying Tomorrow's Materials Today

Cornerstone Research Group, Inc.

ACKNOWLEDGMENT

This presentation summarizes results of Small Business Innovation Research (SBIR) Phase I contract F33615-02-M-5027 (4/9/02 - 11/7/02) and effort to date for Phase II contract F33615-03-C-5013 funded by the Air Force Research Laboratory (AFRL) and managed by Dr. David Mollenhauer (AFRL/MLBC).

OVERVIEW

- Program Introduction
- Phase I Objectives
- Phase I Results
- Phase II Plan
- Phase II Early Results
- Phase II Enhancement
- Summary

Cornerstone Research Group, Inc.

OVERVIEW

- Program Introduction
- Phase I Objectives
- Phase I Results
- Phase II Plan
- Phase II Early Results
- Phase II Enhancement
- Summary

PROGRAM INTRODUCTION

- **Applications: Space-Based Optics**

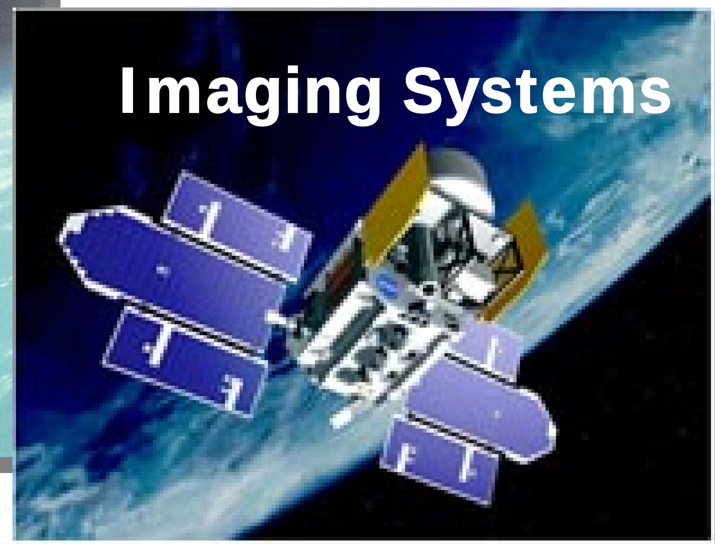
- **Operational Need:**
  Improve on glass & metal mirrors
  - **Lighter**
  - **Tougher**
  - **Cheaper**

Images
L: www.fas.org/spp/starwars/program/sbl.htm
R: www.ball.com/aerospace/prod rs bus.html

Cornerstone Research Group, Inc.

PROGRAM INTRODUCTION

- **Applications: Space-Based Optics**



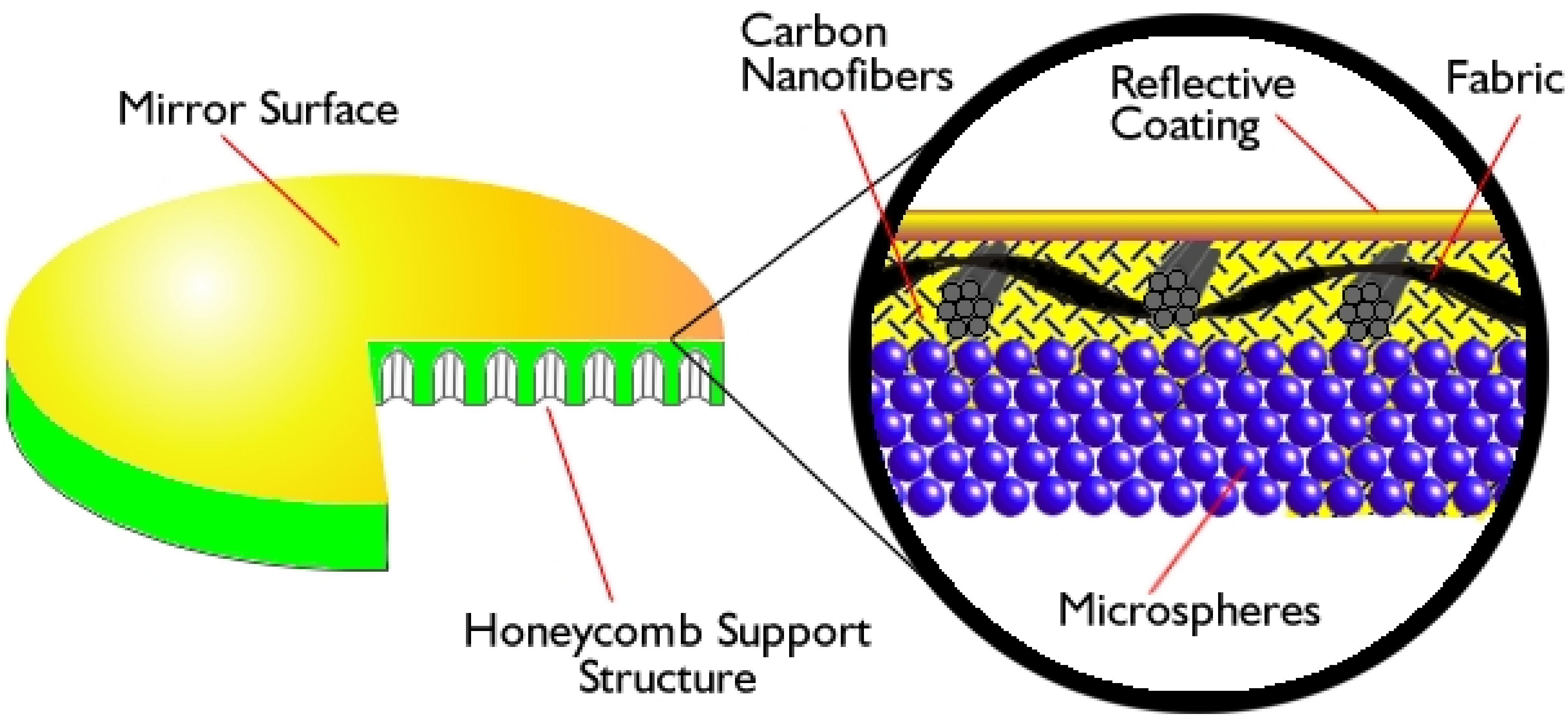
- **Operational Need:**
  Improve on glass & metal mirrors
  - Lighter → new materials
  - Tougher → new materials
  - Cheaper → new processes

PROGRAM INTRODUCTION: Material Design Elements

- **Space compatible:**
  - Radiation hard (to space ambient)
  - AO resistant
    (inherent or through practical coating)
  - Resistant to out-gassing in vacuum
- **Improvement over glass or metal mirrors:**
  - Lower areal density
  - Higher tolerance to thermal excursion (low CTE)
  - Improved strength (toughness & stiffness)
- **Compatible with obtaining optical surface**

PROGRAM INTRODUCTION: Material Concept

Multi-Component Composites



Cornerstone Research Group, Inc.

PROGRAM INTRODUCTION

- **Applications: Space-Based Optics**

- **Operational Need:**
  Improve on glass & metal mirrors
  - **Lighter**
  - **Tougher**
  - **Cheaper**

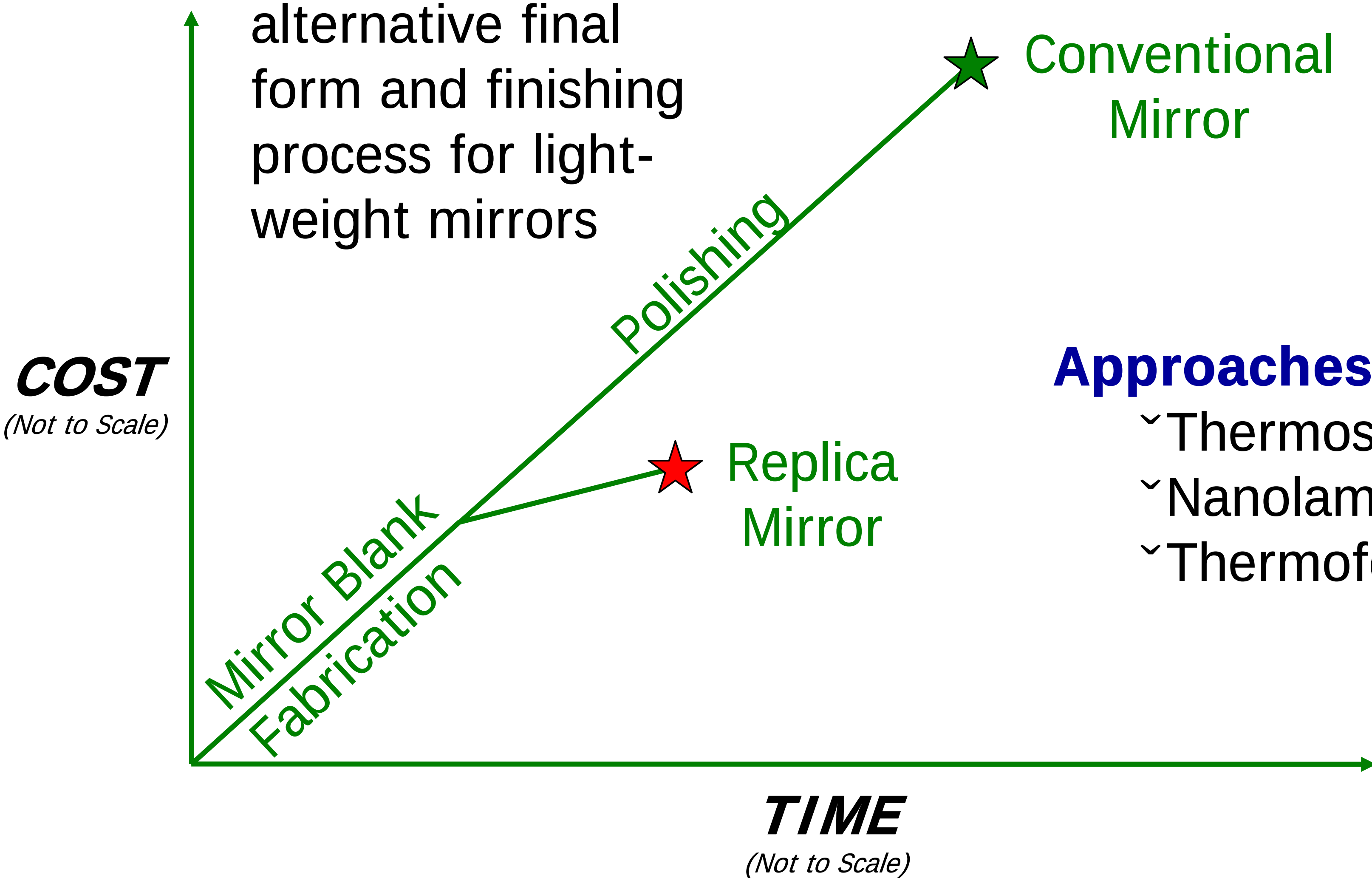
new materials

$\boxed{\textbf{new processes}}$

Cornerstone Research Group, Inc.

PROGRAM INTRODUCTION: Replication Technology

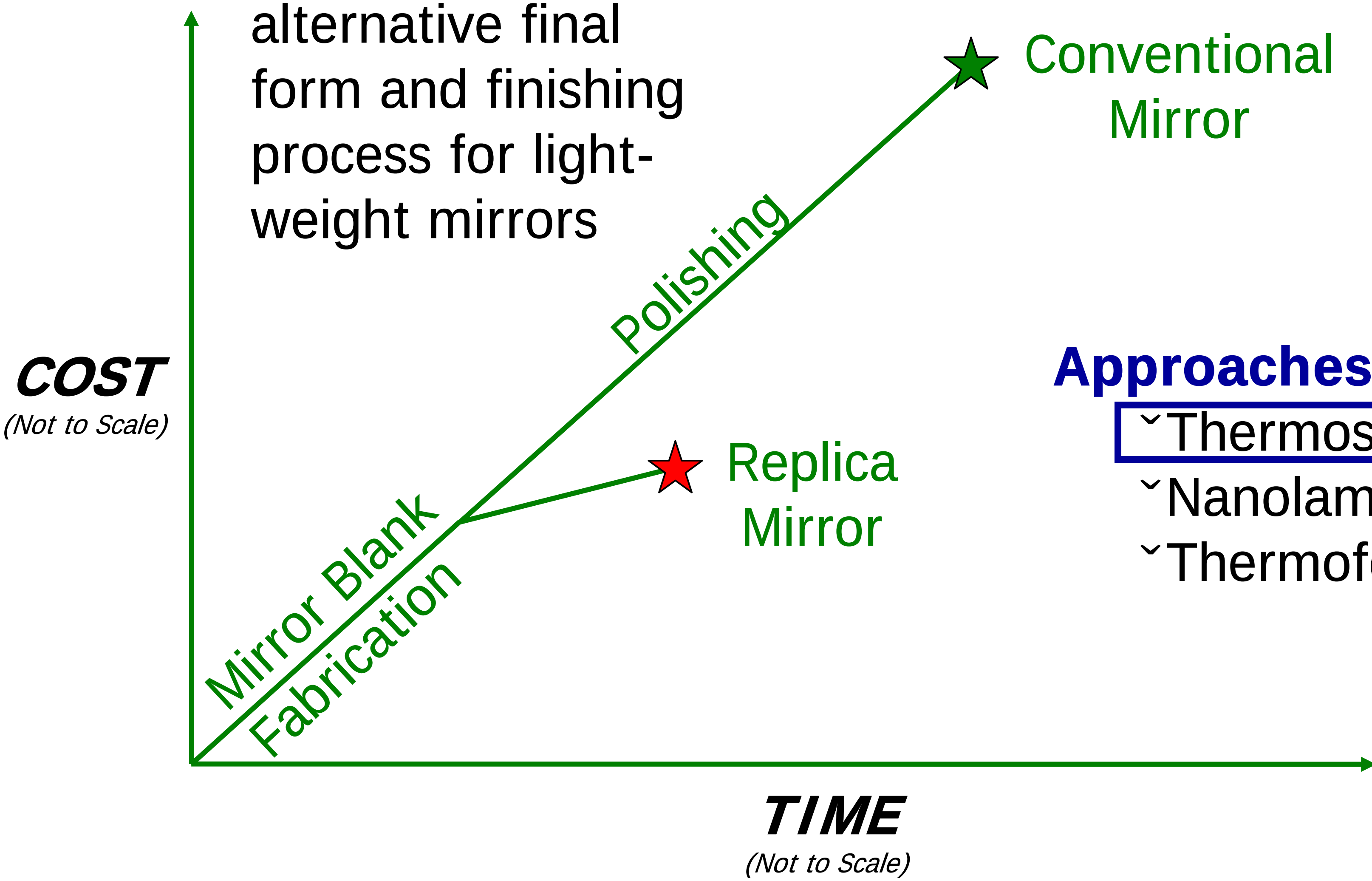
Goal: Develop alternative final form and finishing process for light-weight mirrors



Approaches:
- Thermoset
- Nanolaminate
- Thermoform

PROGRAM INTRODUCTION: Replication Technology

Goal: Develop alternative final form and finishing process for light-weight mirrors



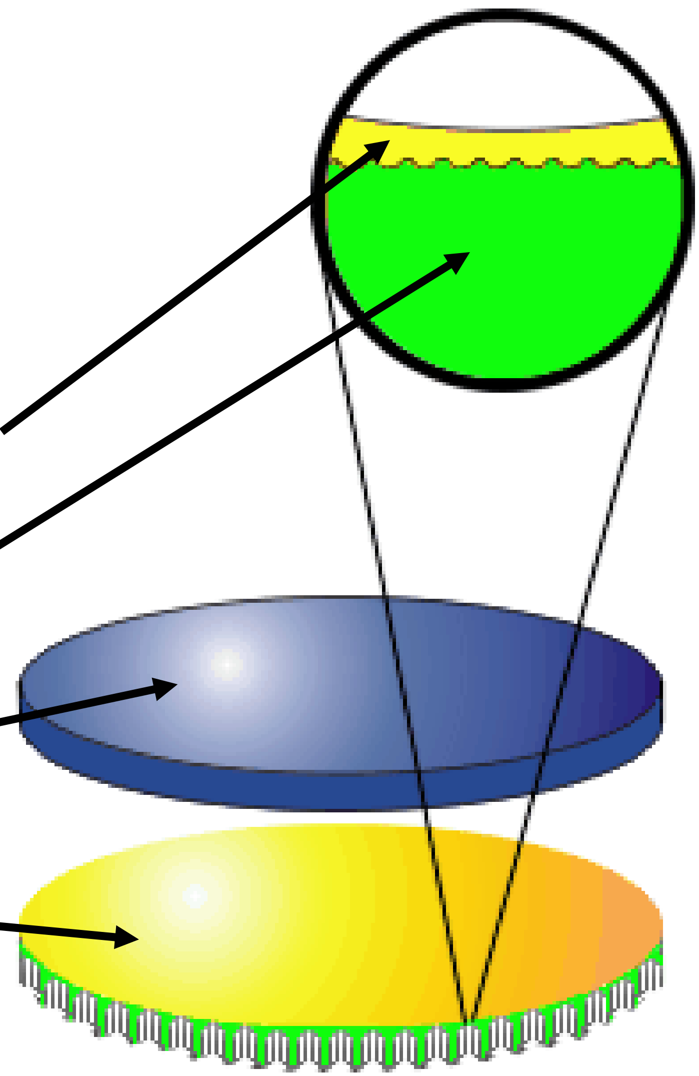
Approaches:

- Thermoset
- Nanolaminate
- Thermoform

Cornerstone Research Group, Inc.

PROGRAM INTRODUCTION: Thermoset Replica Concept

Cast Optical Surface (no grinding or polishing)



Polymer Mirror Surface

Mirror Substrate

Optical Quality Reusable Mold

Released Composite Mirror (final figure & finish)

Cornerstone Research Group, Inc.

OVERVIEW

- Program Introduction
- Phase I Objectives
- Phase I Results
- Phase II Plan
- Phase II Early Results
- Phase II Enhancement
- Summary

Cornerstone Research Group, Inc.

PHASE I OBJECTIVES

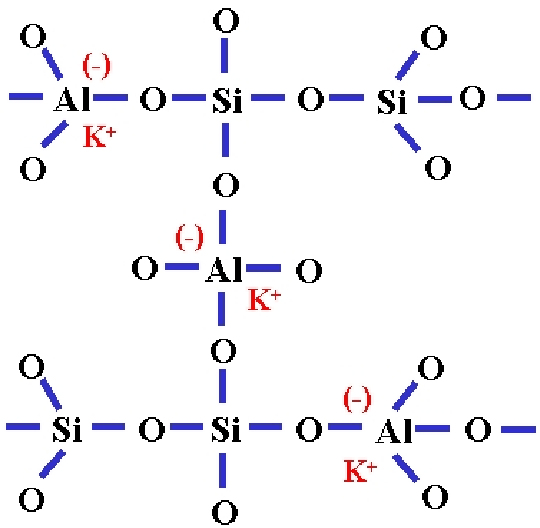
1. **Formulate multi-component composites tailored for space-based mirrors**
2. **Develop fabrication process**
3. **Characterize candidate materials**
4. **Assess candidates' feasibility for space-based mirrors**
5. **Assess candidates' potential for mirror producibility**

Cornerstone Research Group, Inc.

OVERVIEW

- Program Introduction
- Phase I Objectives
- Phase I Results
- Phase II Plan
- Phase II Early Results
- Phase II Enhancement
- Summary

PHASE I RESULTS:
Sialyte™ Inorganic "Resin"



poly(sialate-siloxo)

Attributes

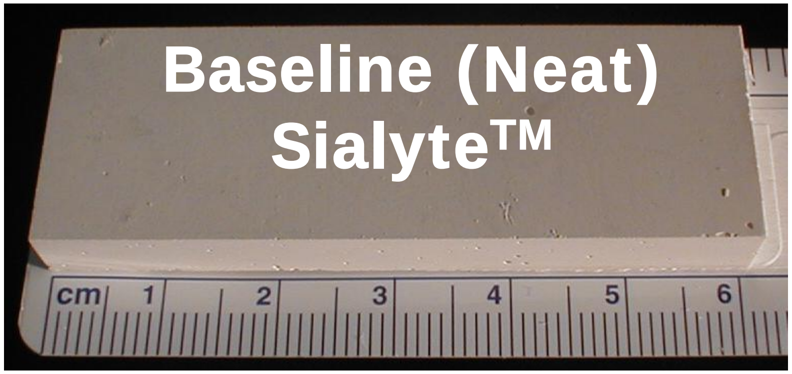
- Inherently space compatible
- Lattice structure: high stiffness
- Operating temp: to ~900 °C bridges gap between organic resin and ceramics
- Low-temp process: fabrication savings

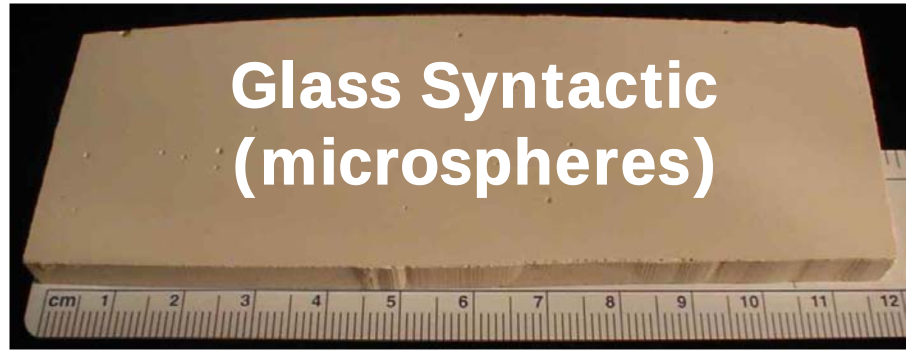
Applications

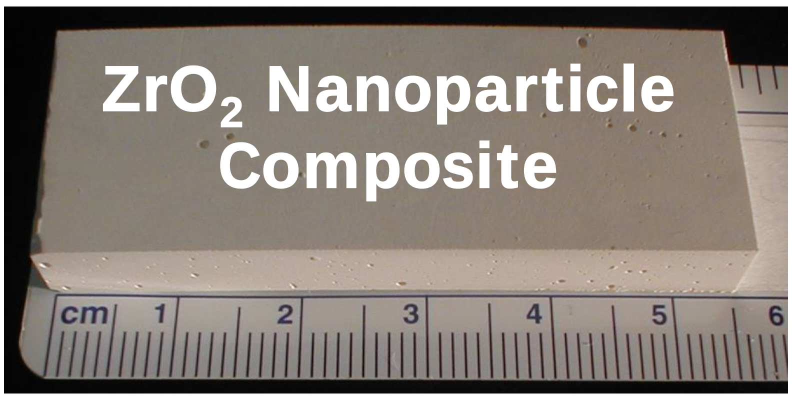
- Space-based structures
- Propulsion components

CRG
Cornerstone Research Group, Inc.

PHASE I RESULTS: Representative Inorganic Candidates







Carbon Nanofiber-Glass Syntactic Laminate

PHASE I RESULTS: Sialyte™ Replica Mirror Coupon

Fabrication

- Sialyte™ cast on optical flat
- Gold coating

Finish

- Porous surface
- Roughness:
  - Best local: ~5 nm RMS (neat)
  - Best overall: ~8 nm RMS (ZrO_2 composite)

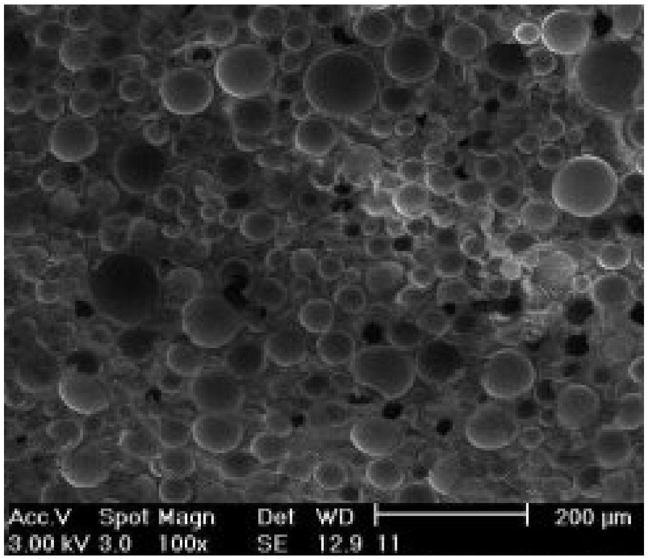
Cornerstone Research Group, Inc.

PHASE I RESULTS: Organic Materials

- **Cyanate ester resin**
  - – Demonstrated space compatible chemistry
  - – Compatible with mature processes demonstrated with epoxy-based materials
    - Streamlines composite design
    - Streamlines process development
  - – Formulation experience:
    Confidence in near term transition

PHASE I RESULTS: High-Performance Syntactic Composite

"Syntactic" = resin matrix + hollow microspheres



Attributes

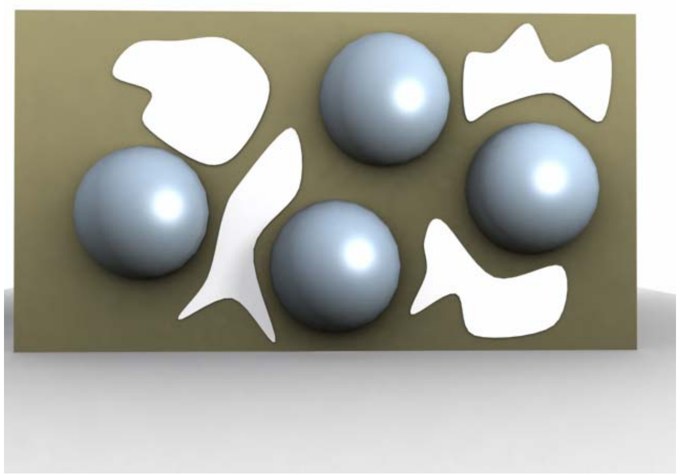
– Low mass density: 0.55 g/cc
– High specific strength: 126 MPa in compression
– Simple fabrication processes

Applications

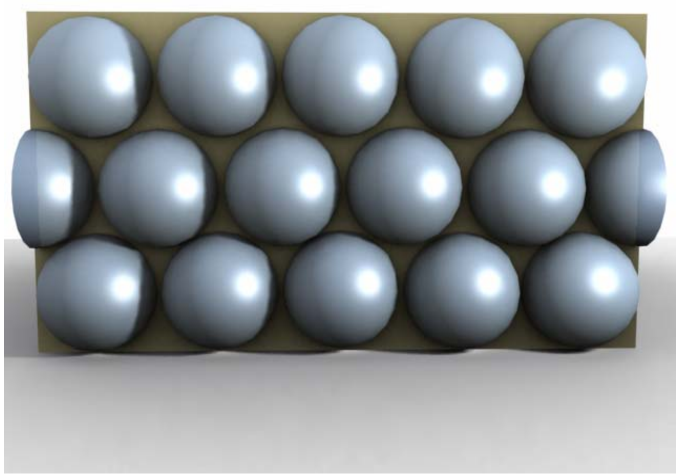
– Lightweight structures
– Low dielectric structures
– High strength insulation

PHASE I RESULTS: High-Performance Syntactic Composite

- **New fabrication technique**
  - Eliminates voids & increases microsphere loading
  - Improved material properties
    - Stronger
    - More uniform & more consistent



Conventional Process

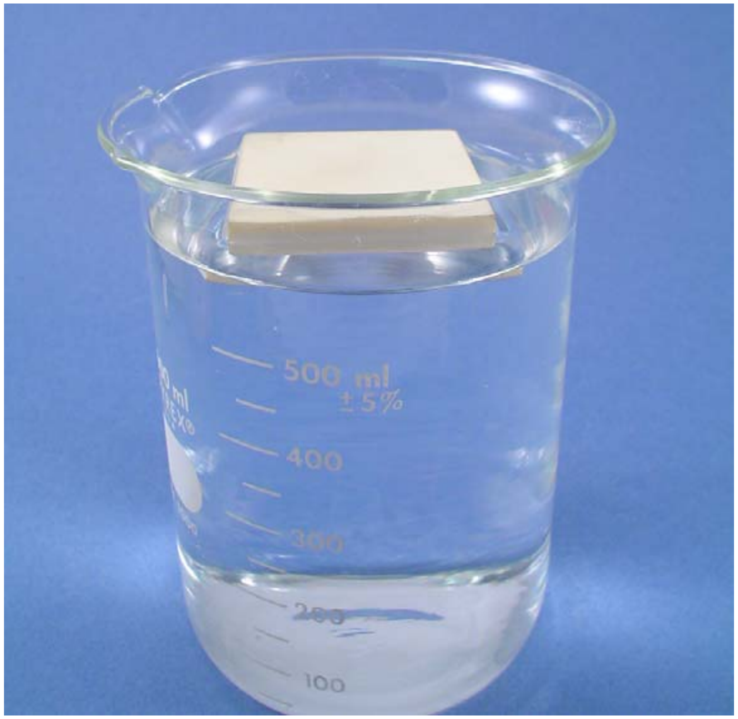


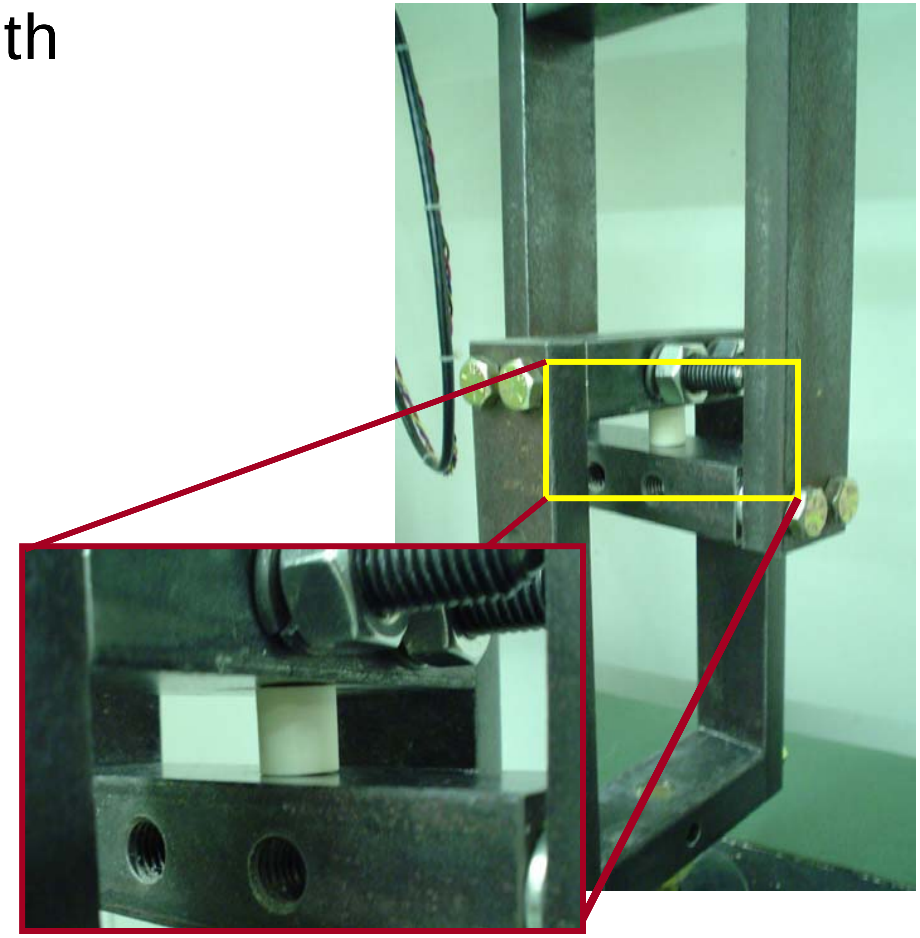
CRG Process

PHASE I RESULTS: High-Performance Syntactic Composite

Advantages for space mirrors

- Very high specific strength
- Low density

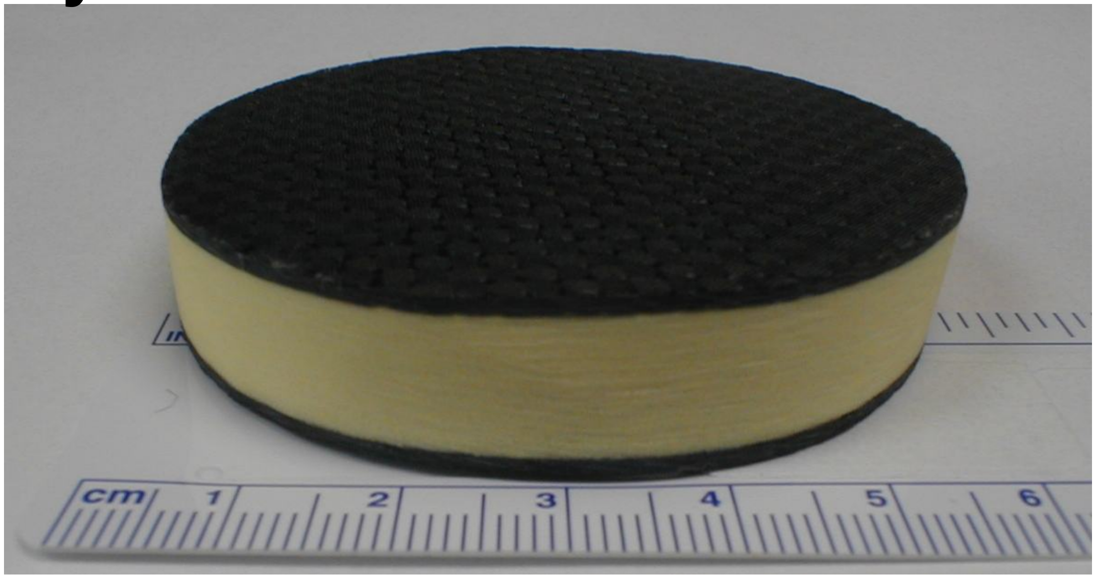




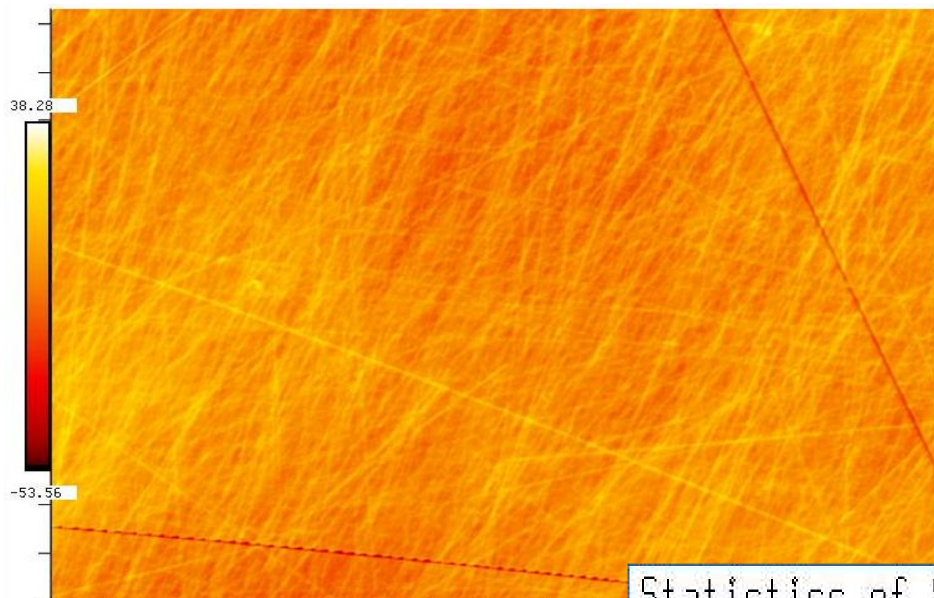
PHASE I RESULTS: Representative Organic Candidates

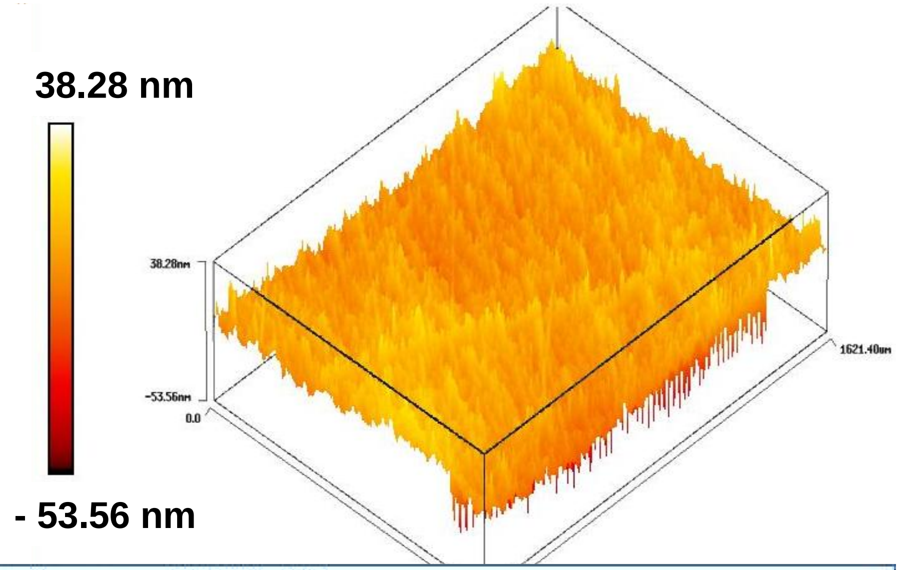
Carbon Nanofiber Reinforcement

Syntactic-Carbon Fiber Laminate



PHASE I RESULTS:
Cyanate Ester Surface Finish



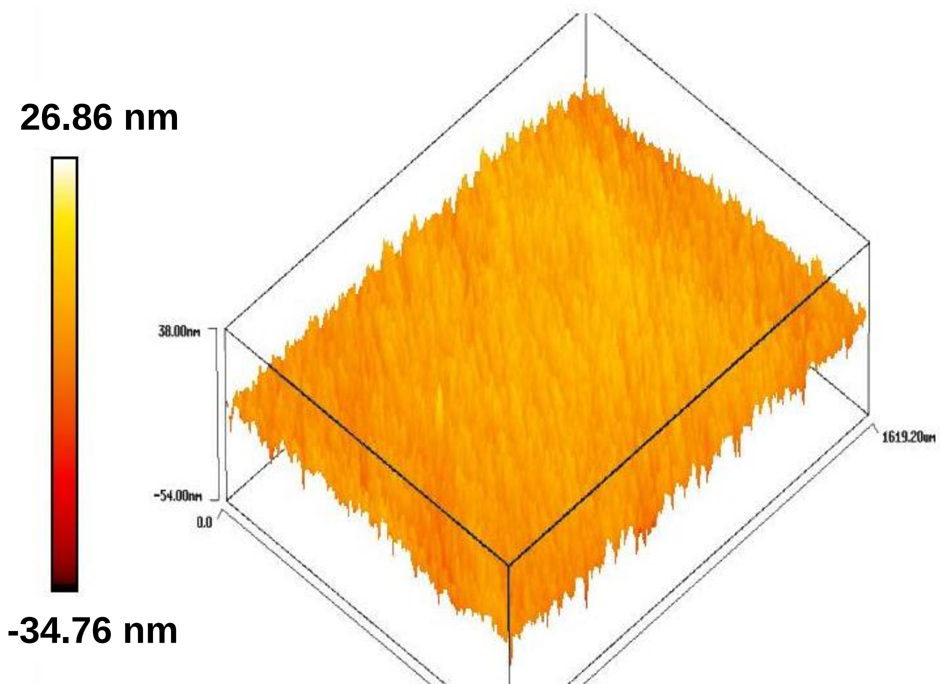


Statistics of Surface: GK40-1A					
Rp:	38.28nm	Rq:	6.09nm	Area:	1621.40x1235.00um
Rv:	-53.56nm	Ra:	4.74nm	Mag :	5.0
PV:	91.84nm	Rsk:	0.05	DATE:	06-14-2002
PT:	350071	Rku:	4.45	TIME:	10:03:38
Terms Subtracted:		Tilt			

Vxuidfh#Jrxjkqhvv=##913<#qp #JPV

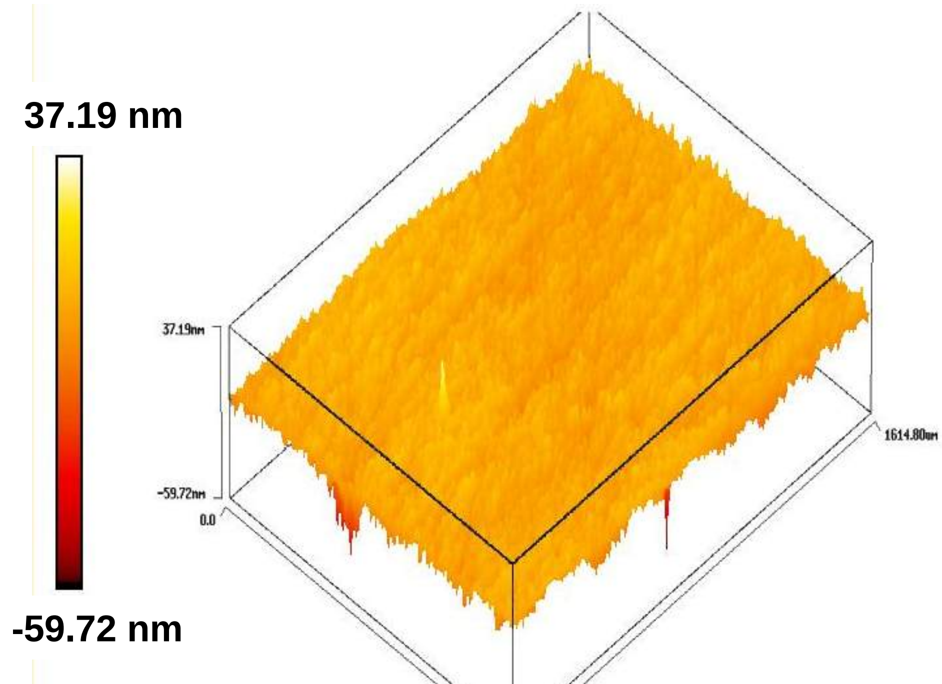
Cornerstone Research Group, Inc.

PHASE I RESULTS: Mold Finish



Statistics of Surface:	PUCK1-A				
Rp:	26.86nm	Rq:	5.41nm	Area:	1619.20x1229.80um
Rv:	-34.76nm	Ra:	4.30nm	Mag :	5.0
PV:	61.62nm	Rsk:	-0.19	DATE:	06-13-2002
PT:	348127	Rku:	3.16	TIME:	09:29:50
Terms Subtracted:		Tilt			

Urxjkqhvv#Ehiruh#Fdwlqj=##
8174#qp #UPV



Statistics of Surface:	PUCK1-B				
Rp:	37.19nm	Rq:	4.61nm	Area:	1614.80x1229.80um
Rv:	-59.72nm	Ra:	3.59nm	Mag :	5.0
PV:	96.91nm	Rsk:	-0.65	DATE:	06-14-2002
PT:	347182	Rku:	5.65	TIME:	11:56:13
Terms Subtracted:		Tilt			

Urxjkqhvv#Diwhu#Fdwlqj=##
7194#qp #UPV

PHASE I RESULTS: Cyanate Ester - Syntactic Mirror

Cornerstone Research Group, Inc.

OBJECTIVE

Demonstrate feasibility of replication approach

RESULTS

Form

Slight curvature (due to cure shrinkage)

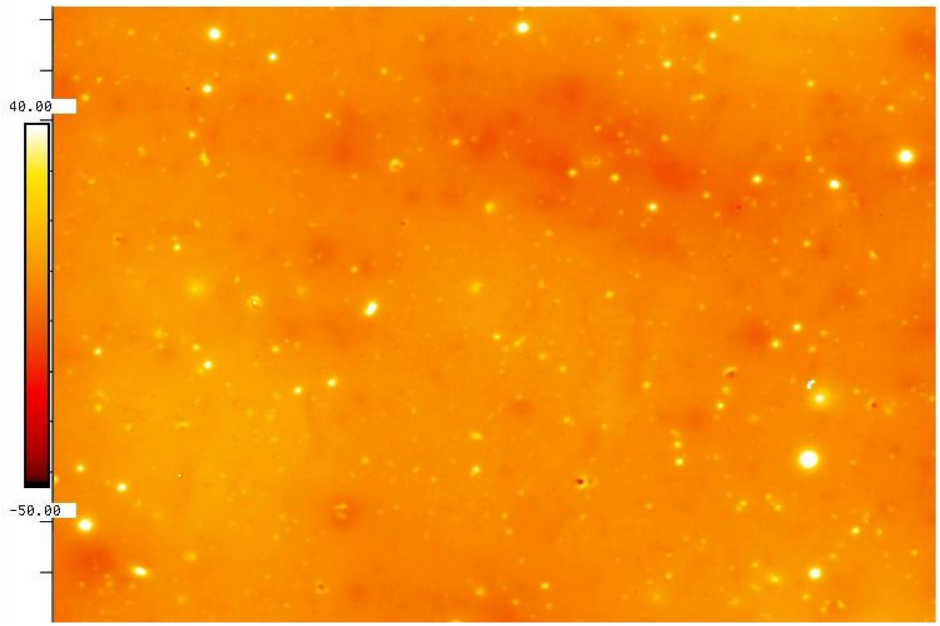
Finish

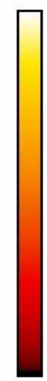
- Good mold replication
- Good reflective coating

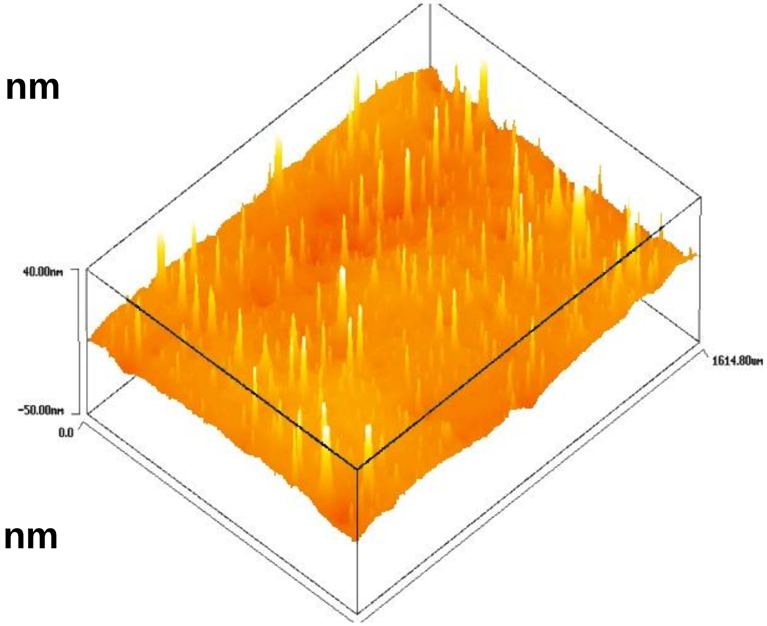
Fabrication

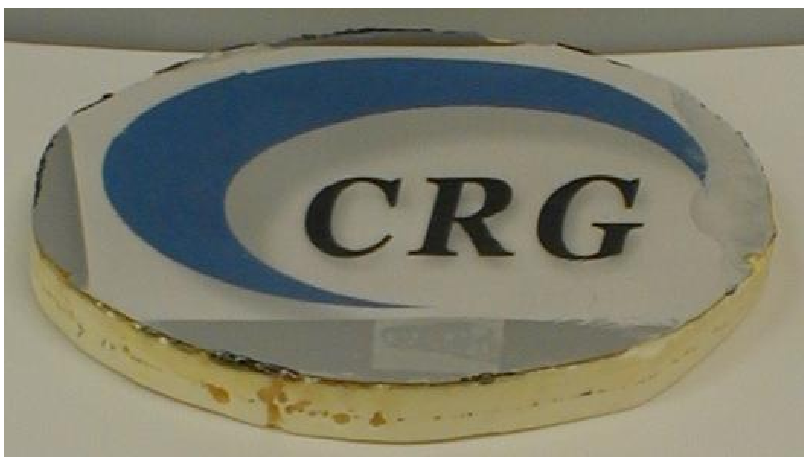
- Good mold release
- Process development needed to improve figure replication
- Initial feasibility established

PHASE I RESULTS:
Cyanate Ester - Syntactic Mirror









Statistics of Surface: GK84-B					
Rp:	166.37nm	Rq:	5.15nm	Area:	1614.80x1229.80um
Rv:	-32.51nm	Ra:	3.29nm	Mag :	5.0
PV:	198.88nm	Rsk:	5.13	DATE:	09-05-2002
PT:	347168	Rku:	91.18	TIME:	15:18:39
Terms Subtracted:		Tilt			

Vxuidfh#Urxjkqhvv=##
814 8#qp #UP V

PHASE I RESULTS: Summary

- **Sialyte™ Inorganic Composites**
  - Multi-component composites feasible
  - Attributes promising for space mirrors
  - Need further development to reach transition

- **Cyanate Ester Organic Composites**
  - Multi-component composites feasible
  - Attributes demonstrated for replica mirrors for space-based optics
  - Ready for transition demonstration

Cornerstone Research Group, Inc.

OVERVIEW

- Program Introduction
- Phase I Objectives
- Phase I Results
- $\boxed{\text{Phase II Plan}}$
- Phase II Early Results
- Phase II Enhancement
- Summary

PHASE II PLAN: Technical Objectives

1. Develop mature composite systems for replica mirrors (RM)
   a. Organic materials
   b. Inorganic materials
2. Develop mature fabrication processes for RM
3. Develop practical design methodology for RM
4. Demonstrate a prototype composite RM

Cornerstone Research Group, Inc.

PHASE II PLAN: Tasks in Progress

- Optimize organic composites for replica mirrors
  - Materials
  - Processing
- Optimize inorganic composites for replica mirrors
  - Materials
  - Processing
- Mirror development
  - Structural design
  - Composite cutting
  - Fabrication (assembly and bonding)
  - Reflective surface
- Characterize materials and mirrors

Cornerstone Research Group, Inc.

OVERVIEW

- Program Introduction
- Phase I Objectives
- Phase I Results
- Phase II Plan
- Phase II Early Results
- Phase II Enhancement
- Summary

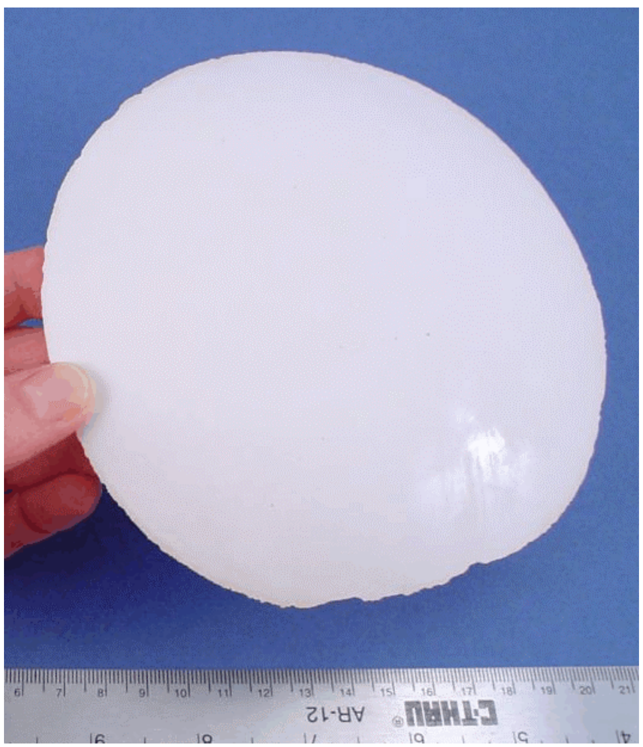
PHASE II EARLY RESULTS: Inorganic Materials

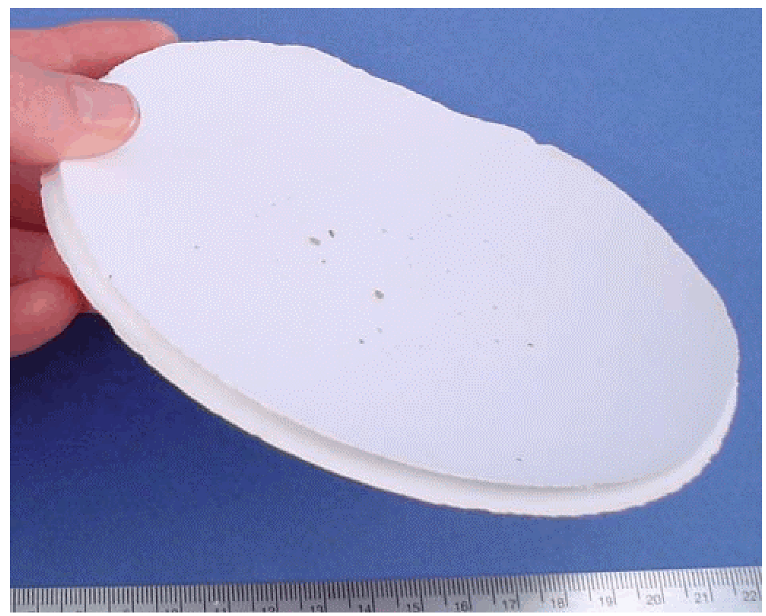
Vfdolqj#xs#surfhvvhv#) #rswlp l}lqj#frp srvlwhv

CRG
Cornerstone Research Group, Inc.

PHASE II EARLY RESULTS: Inorganic Materials

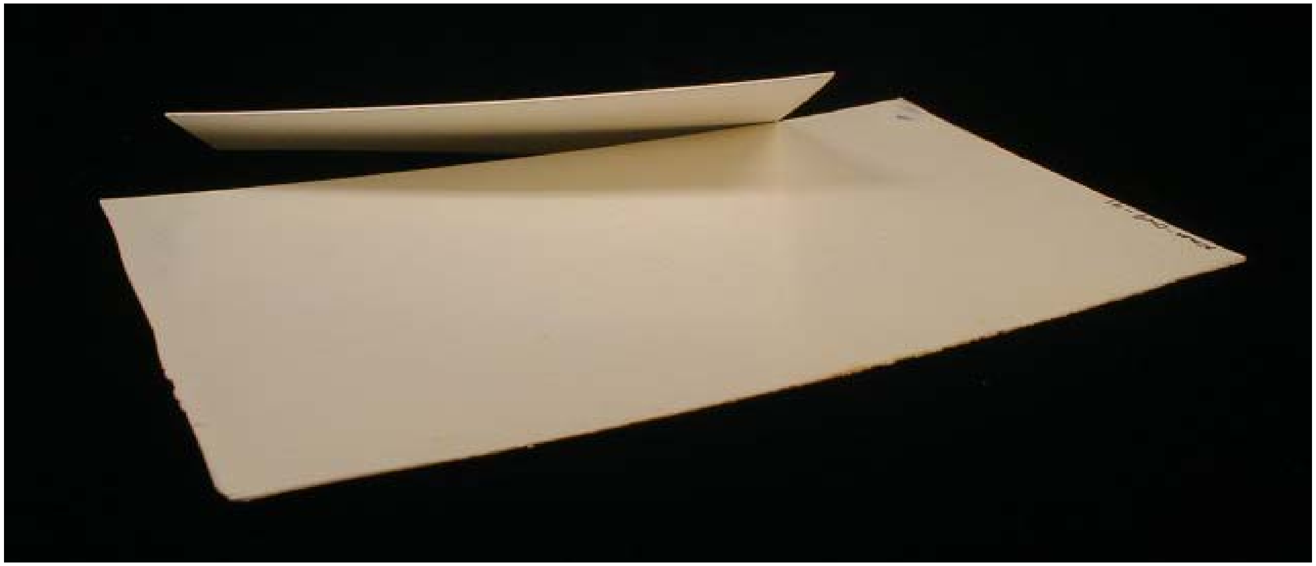
- Processing improvements
  - Better control and repeatability over Phase I manual techniques
  - Developing techniques for complex shapes





PHASE II EARLY RESULTS: Organic Materials

- Syntactic materials
  - Process improvement & scale-up on track
    - Thinner & more uniform sheets
    - Larger sheets
  - Enabling technology for new **SynLam™** material



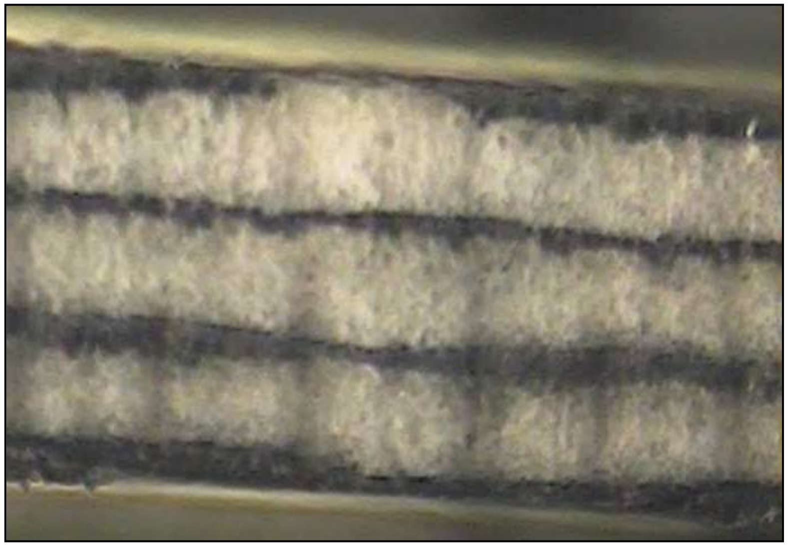
PHASE II EARLY RESULTS: Organic Materials

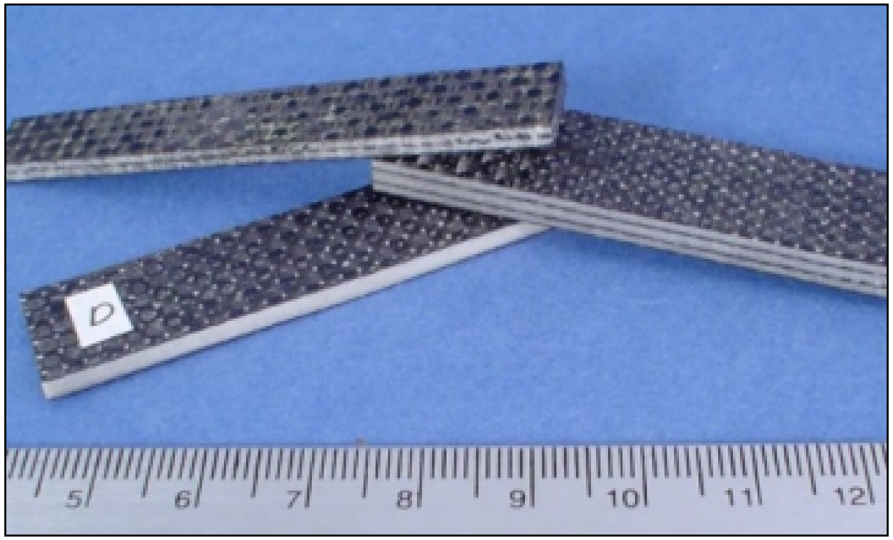
- **SynLam**™ developed for mirror structure:

  Syntactic **Lam**inate composite

  – Syntactic sandwich cores

  – Fiber-reinforced face sheets





Cornerstone Research Group, Inc.

PHASE II EARLY RESULTS: Organic Materials

- **SynLam™** Advantages
  - Lightweight
  - Maximum operating temperature 200 °C
  - 50% greater specific stiffness than conventional carbon fiber composite

	Specific Flexural Strength	Specific Stiffness
SynLam™	371 MPa (54 kpsi)	33 GPa (4786 kpsi)
Carbon Composite	362 MPa (52 kpsi)	22 GPa (3191 kpsi)

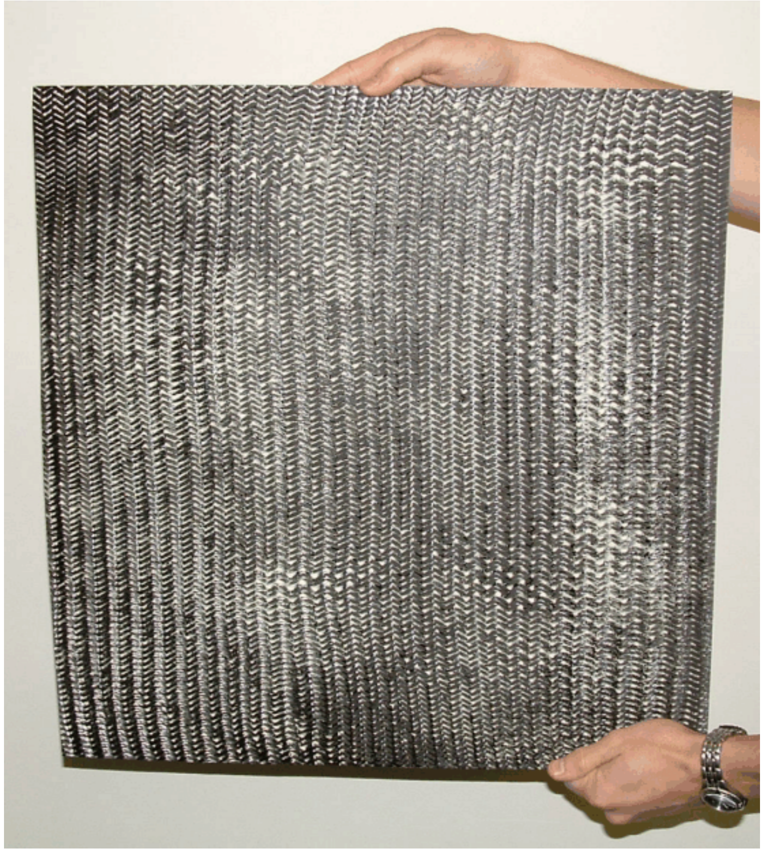
PHASE II EARLY RESULTS: Organic Materials

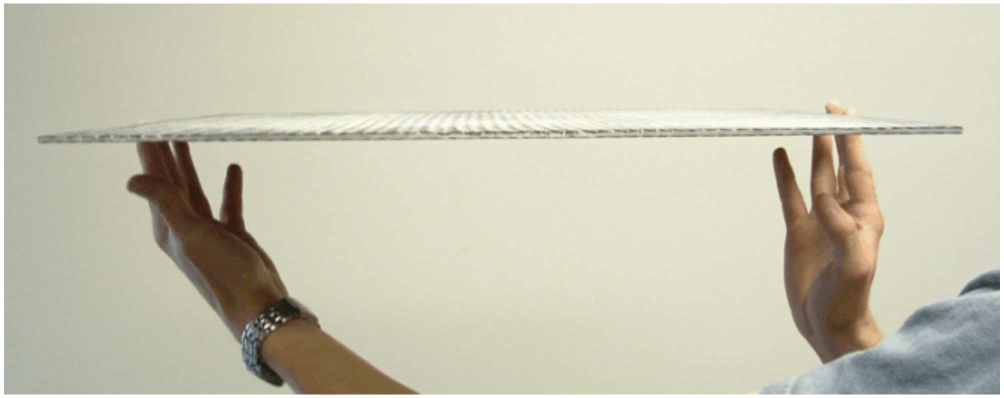
- SynLam™ Scaled Up:

  From hand lay-up to automation

  – Cyanate ester resin: 0.5 m x 0.5 m x 0.5 cm

  – Epoxy resin: 0.9 m x 0.9 m x 0.5 cm





Cyanate Ester SynLam™

PHASE II EARLY RESULTS:
Organic Materials

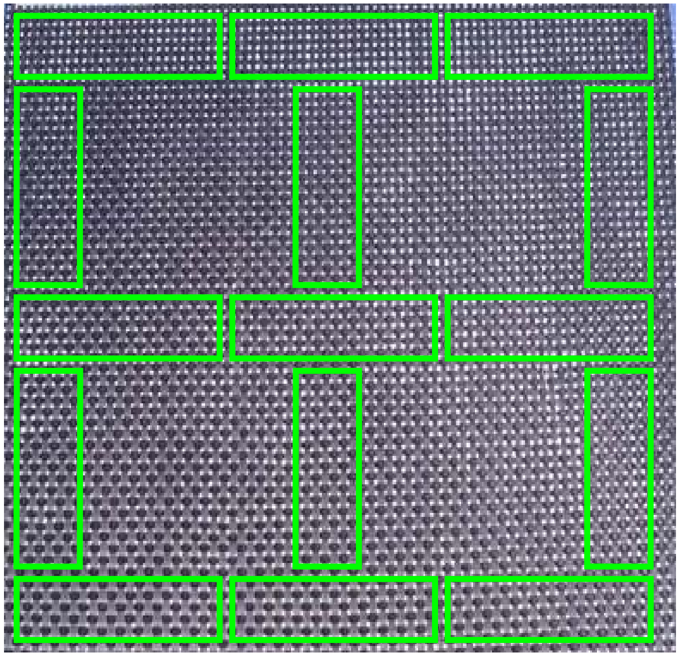
- Ongoing process development:
  Complex SynLam™ Structures

PHASE II EARLY RESULTS: Organic Materials

- Ongoing process development:

  Quality Control

  - Current SynLam™ Uniformity (1/3 m scale sheets):
    - Density ± 1%
    - Thickness ± 2%
    - Specific modulus ± 2%

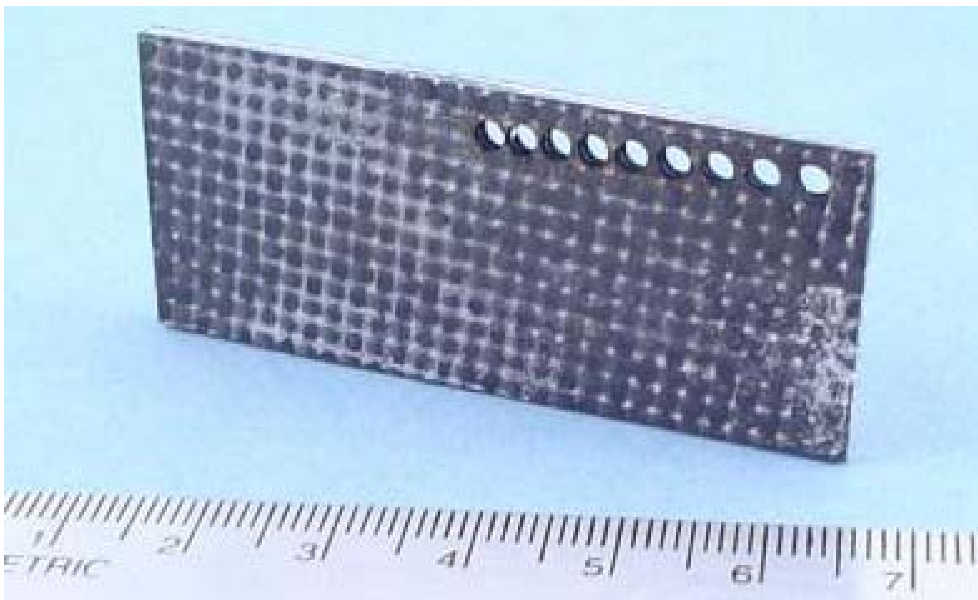


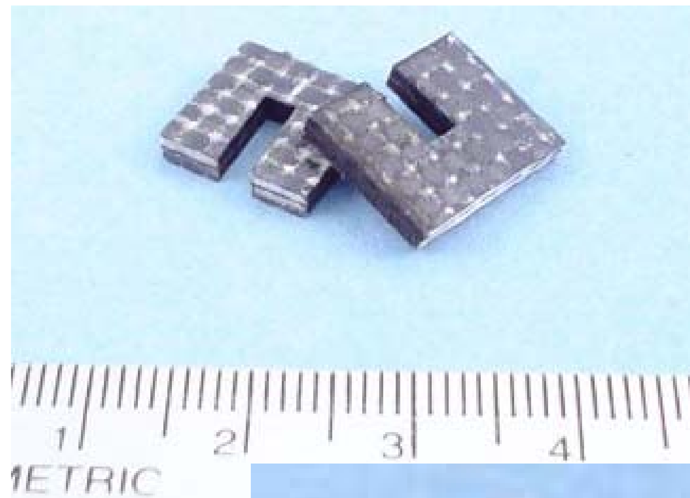
CRG
Cornerstone Research Group, Inc.

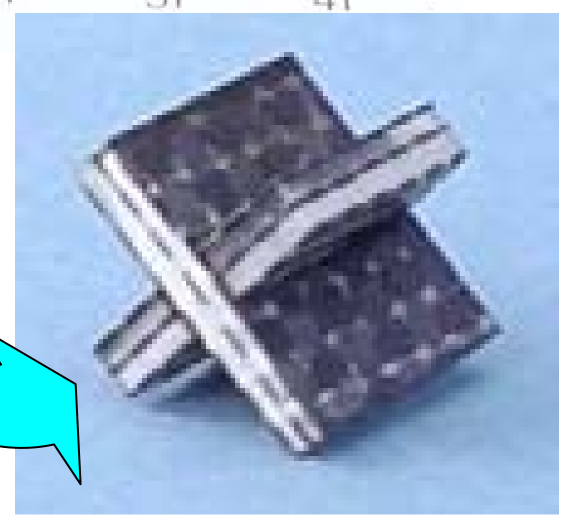
PHASE II EARLY RESULTS: Organic Materials

- Ongoing process development:

  Laser machining to cut SynLam™

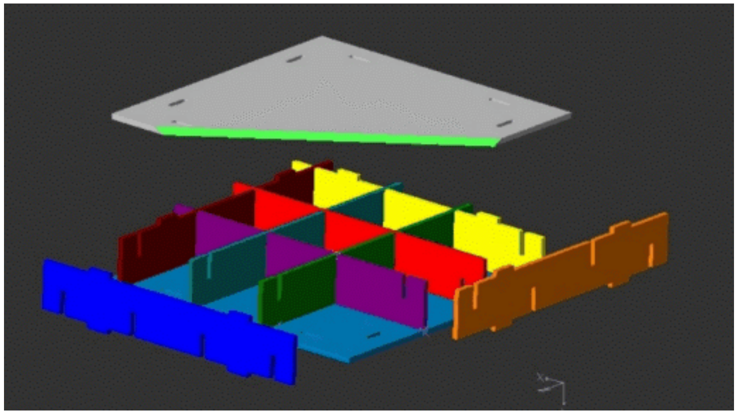




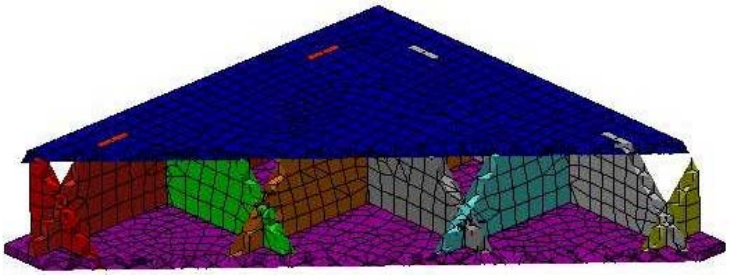


CRG
Cornerstone Research Group, Inc.

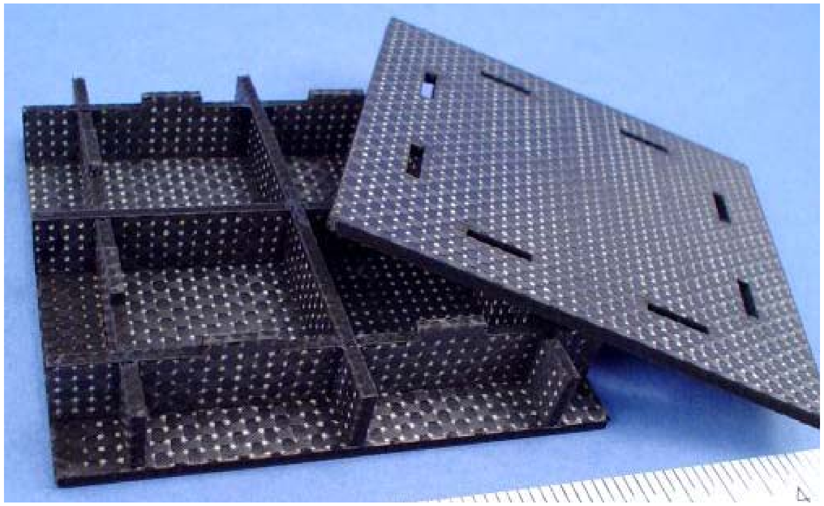
PHASE II EARLY RESULTS: Mirror Development



Design



FE Analysis



Fabrication

Coupon-Scale (8 cm across)

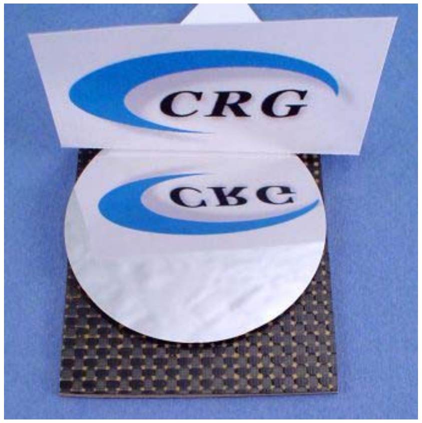
SynLam™ Structure

Areal Density = 3.2 kg/m²

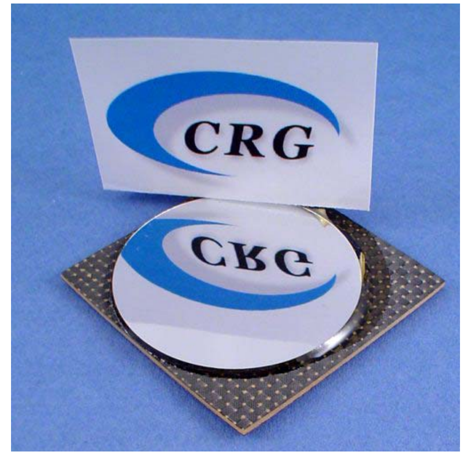
Cornerstone Research Group, Inc.

PHASE II EARLY RESULTS: Mirror Development

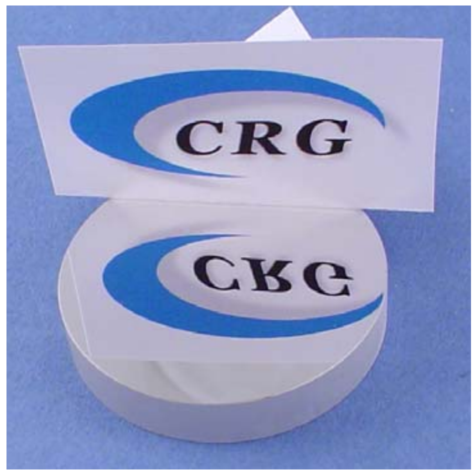
Cast Thermoset Replication



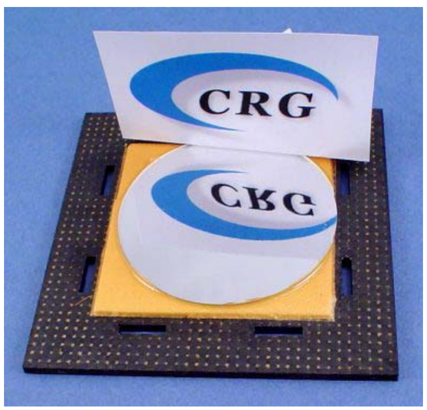
Early Mirror (Print Through)



Mirror w/CE Resin Buffer Layer



Mold with Release Coating

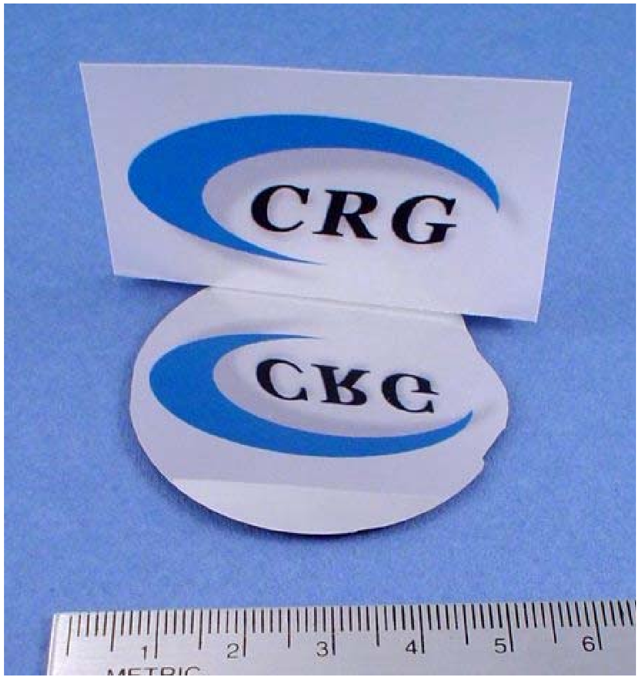


Mirror w/Syntactic Buffer Layer

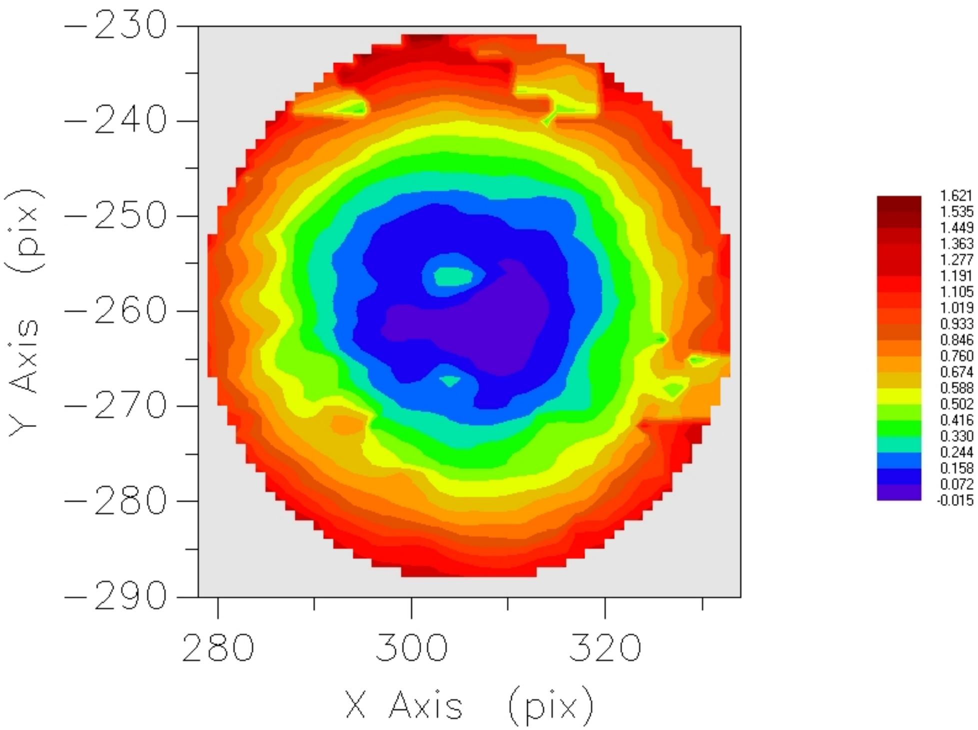
Mirror on CE MWNT Composite

Cornerstone Research Group, Inc.

PHASE II EARLY RESULTS: Mirror Development



Symmetric Figure



Range (PV) = 1.6358 waves, RMS = 0.3501 waves, Strehl = 0.0079
Analysis Aper: Pos[306, 260] Size[57, 60]

Development Progressing Rapidly

Cornerstone Research Group, Inc.

PHASE II EARLY RESULTS: Mirror Development

- Current challenges
  - Improving optical surface
  - Interface between substrate and optical surface
  - Internal bonding of mirror structure (print-through issue)
  - Scale-up to prototype size

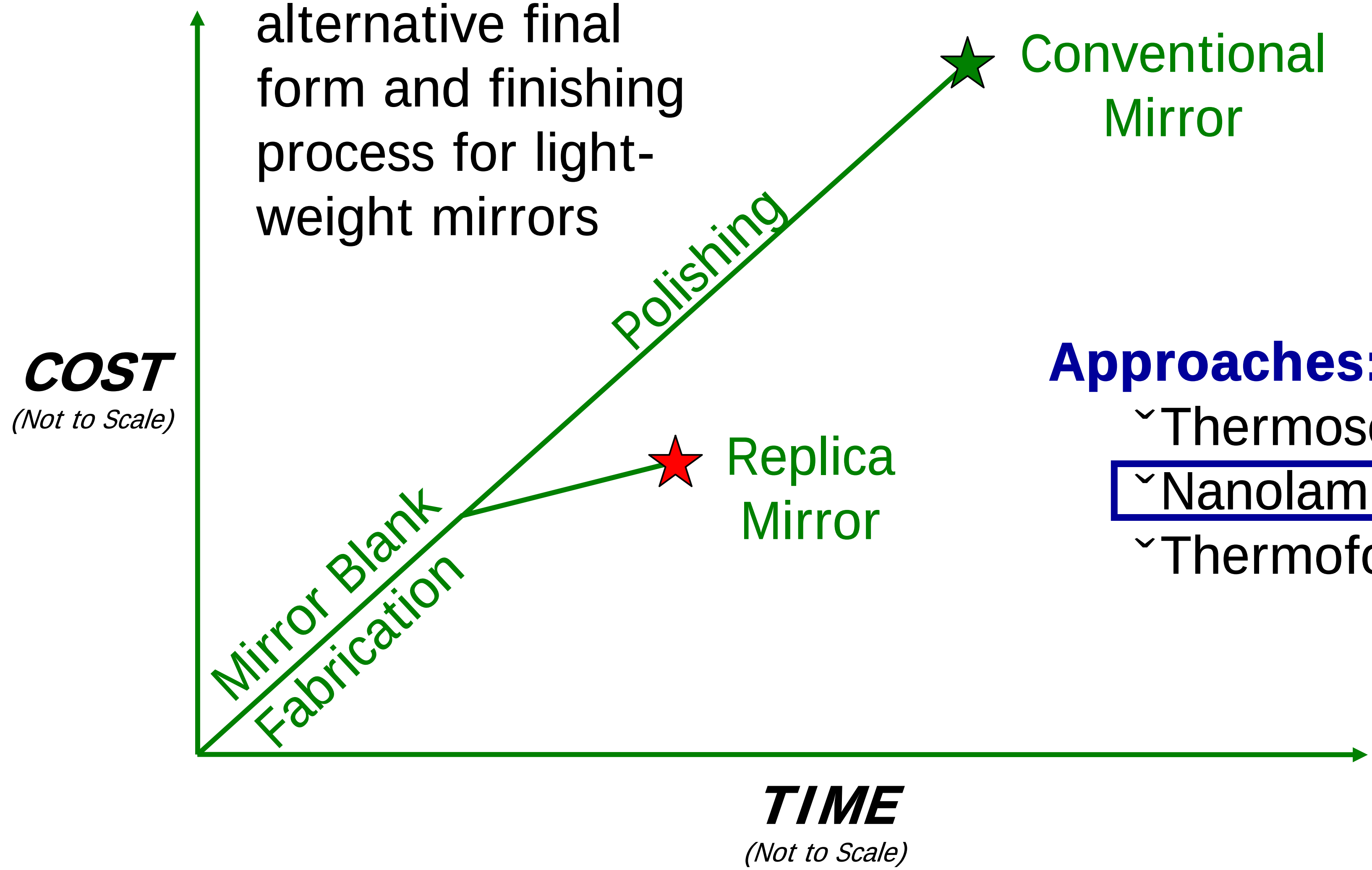
Cornerstone Research Group, Inc.

OVERVIEW

- Program Introduction
- Phase I Objectives
- Phase I Results
- Phase II Plan
- Phase II Early Results
- Phase II Enhancement
- Summary

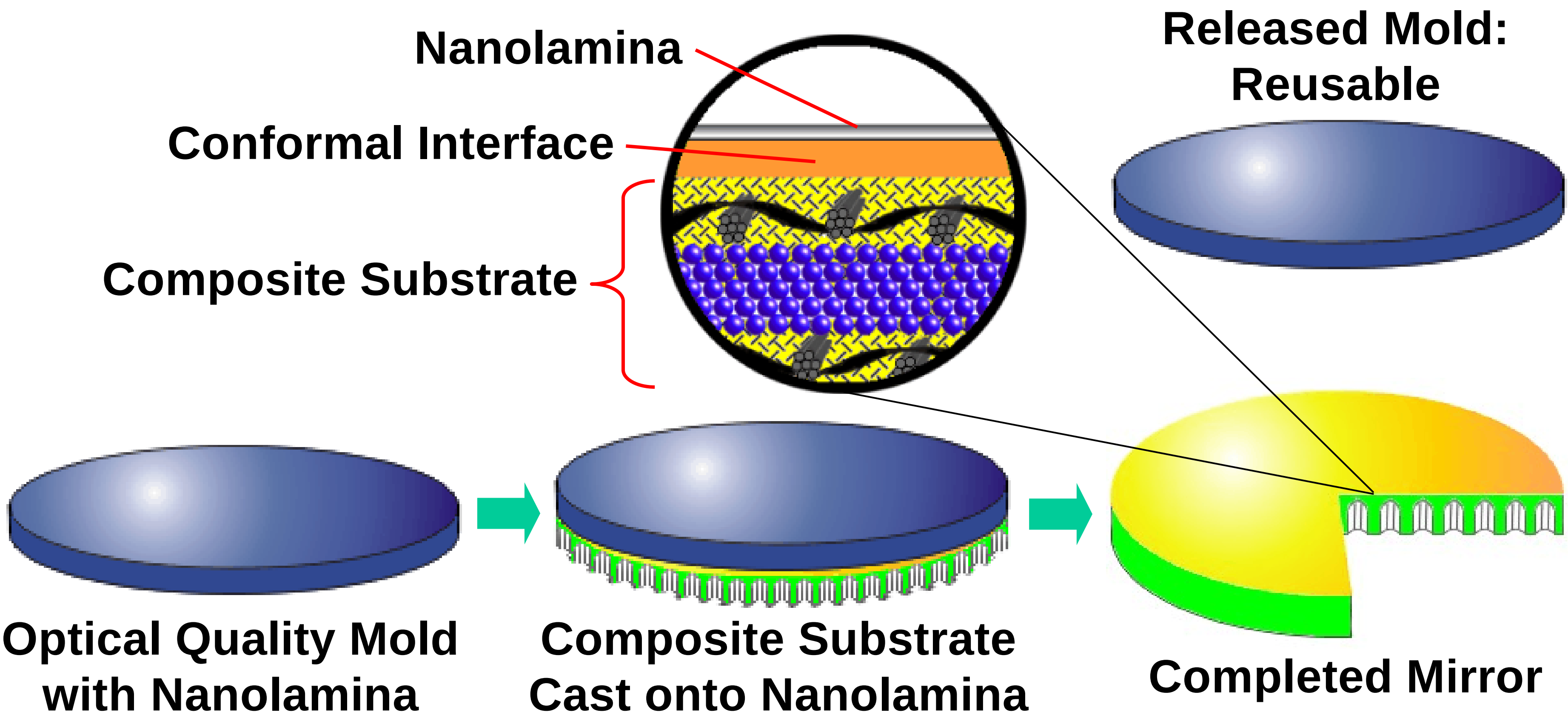
PROGRAM INTRODUCTION: Replication Technology

Goal: Develop alternative final form and finishing process for light-weight mirrors



Approaches:
- Thermoset
- Nanolaminate
- Thermoform

PHASE II ENHANCEMENT: Nanolaminate Replica Concept



PHASE II ENHANCEMENT: Approach

- Demonstrate Feasibility
  - Tailor materials for compatibility
  - Develop process for integrating lamina with structure
  - Evaluate thermal & optical performance
    - Quality of figure & finish at steady state
    - Stability during thermal cycling
- Demonstrate prototype replica mirror
  - 15 cm flat
  - Specular reflection
  - Cost-effective reusable tooling
- Effort commenced 15 June 2004

OVERVIEW

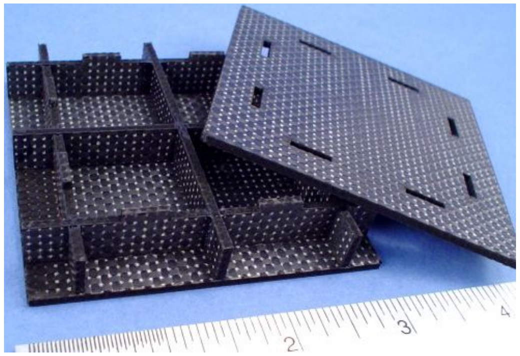
- Program Introduction
- Phase I Objectives
- Phase I Results
- Phase II Plan
- Phase II Early Results
- Phase II Enhancement
- Summary

PHASE II SUMMARY: Early Results

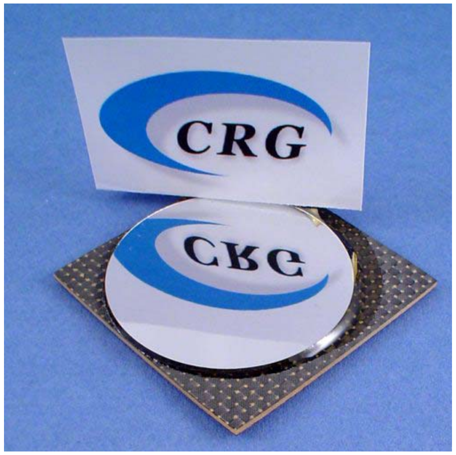
Cornerstone Research Group, Inc.

- **Sialyte™ Inorganic Composites**
  - Appear promising for space mirrors
  - Development progressing

- **Cyanate Ester Organic Composites**
  - SynLam™ selected for structure
  - Optimizing & scaling up



- **Replication Processes**
  - Thermoset approach progressing
  - Nanolaminate approach pending



Cornerstone Research Group, Inc.

PHASE II SUMMARY

Composite Replica Mirrors for Lightweight Space Optics

- Operational Benefits
  - Reduced mirror areal density
  - Tougher & stronger mirrors
  - Reduced fabrication time & cost
- Potential Air Force Applications
  - Space-based imaging systems
  - Space-based directed energy systems
- Potential Commercial Applications
  - Commercial imaging systems (e.g., LANDSAT)
  - Consumer telescopes